

DROPLET COMBUSTION IN A SLOW CONVECTIVE FLOW

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INTRODUCTION

The influences of slow convective flow on droplet combustion, particularly in the low Reynolds number regime, have received very little attention in the past. Most studies in the literature are semi-empirical in nature and they were motivated by spray combustion applications in the moderate to high Reynolds number regime. None of the limited number of fundamental theoretical studies applicable to low Reynolds numbers have been verified by rigorous experimental data. Moreover, many unsteady phenomena associated with fluid-dynamic unsteadiness, such as impulsive starting or stopping of a burning droplet, or flow acceleration/deceleration effects, have not been investigated despite their importance in practical applications. In this study we investigate the effects of slow convection on droplet burning dynamics both experimentally and theoretically. The experimental portion of the study involves both ground-based experiments in the drop towers and future flight experiments on board the International Space Station. Heptane and methanol are used as test fuels, and this choice complements the quiescent-environment studies of the Droplet Combustion Experiment (DCE). An analytical model that employs the method of matched asymptotic expansions and uses the ratio of the convective velocity far from the droplet to the Stefan velocity at its surface as the small parameter for expansion ϵ has also been developed as a part of this investigation. Results from the ground-based experiments and comparison with the analytical model are presented in this report.

EXPERIMENTS

Three separate experimental configurations were examined to generate slow convective flows past a burning droplet in microgravity in preparation for the flight experiment. The first configuration, used in the 2.2 Second Drop-Tower Facility employed a “flow tunnel” powered by a pressurized gas bottle to establish a uniform flow field around a droplet suspended at the end of a fiber. Initial droplet diameters for these tests were approximately 1.0 mm to 1.5 mm. The second test configuration, designed for use in the Zero-Gravity Facility (ZGF, the larger drop tower providing up to 5 seconds of microgravity), utilized a translating mechanism to move the droplet at very precise velocities through a quiescent medium to generate a uniform flow field. The velocities for this system ranged from 0 cm/s to 3 cm/s and initial droplet diameters were nominally 2.3 mm. The third test configuration was designed to fly on the KC-135 aircraft, which provides around 20 seconds of microgravity, and it employed a flow-tunnel concept similar to the 2.2 second tower. However, rather than using pressurized bottles of gas with a sonic orifice, a fan was used to generate the required flows. In this test configuration only two flow velocities were used (i.e., 5 cm/s and 10 cm/s) and the initial droplet diameters were considerably larger at approximately 3 mm.

Tests were run for both n-heptane and methanol in the first two test configurations and for only n-heptane in the KC-135 experiments. Two wide-band radiometers (i.e., 0.6 μm to 40 μm) were used in each experimental configuration in the drop towers to obtain measurements of the gas phase radiative losses. A single wide-band radiometer was used in the KC-135 experimental rig. All radiometers were calibrated against a blackbody source at distances equal to the distance from the droplet support fiber employed in the experimental rigs. The backlit images of the droplet as well as the color images of the flames were obtained during these experiments. Further details of the experiments can be found in [1].

ANALYSIS

An idealized model for droplet vaporization or combustion in the Burke-Schumann reaction-sheet approximation is analyzed in terms of a Peclet number based on the Stefan velocity, taken to be of order unity, for Lewis numbers of unity and for small values of a parameter ε , defined as the ratio of the convective velocity far from the droplet to the Stefan velocity at its surface. Asymptotic solutions for the velocity, pressure and mixture-fraction fields are obtained through second order in ε . All earlier studies (see, e.g., [2-4]) treated the Reynolds number of convection as the small parameter. The present analysis is different in principle because a different small parameter is selected, namely the ratio, ε , of the convection velocity of the gas at infinity to the velocity of the gas at the droplet surface without nonspherical convection. The mathematical development therefore is different and precludes addressing the limit of a nonvaporizing droplet. This selection was made with a view towards the problem intended to be studied. Despite this difference, the resulting expansions contain all the elements in most of the earlier analyses, some of which explicitly refer to a "large radial velocity" and become equivalent mathematically to the present development with appropriate restrictions. The present expansions thus retain essentially the same range of applicability as earlier analyses, and the resulting alternative development given here can help to clarify possible differences associated with different expansion procedures. The results of this analysis are employed to calculate the effects of convection on the burning rate and on the flame shape. Qualitative comparisons with experiment help to identify the strengths and limitations of this model. The reader is referred to an earlier paper [5] for a more detailed discussion of the formulation used in this analysis.

RESULTS AND DISCUSSION

The burning-rate constant, K , the slope of the graph of the square of the droplet diameter as a function of time, was determined for each test run for which ε is smaller than one. Figure 1 shows the comparison between the experimental measurements and the predictions of the current asymptotic analysis, where $(K/K_0 - 1)$ is plotted against the square root of Reynolds number based on droplet radius ($Re = U_\infty R / \nu_\infty$). Here U_∞ is the imposed flow velocity, R is the droplet radius, ν_∞ is the kinematic viscosity, and K_0 is the burning rate constant when there is no flow. A K_0 value of 0.75 mm^2/s was employed in Fig. 1, although a somewhat higher value (probably 0.8 mm^2/s , within experimental accuracy) would be more appropriate, as suggested theoretically and by the data point at $Re=0$ in the figure. Also, in calculating the Reynolds number the kinematic viscosity was taken to be that of air at a mean temperature of 850K, although a somewhat higher mean temperature (perhaps as high as 1200K) may be more appropriate, which would move the data points in the figure to smaller values of Re . Since the present theory does not account for

variable properties, it is essential in comparisons to make an adjustment of this type; if the theoretical formula is used with v_∞ evaluated at the ambient temperature of about 300K, then the slope of the theoretical line is much too steep. In view of the uncertainties in K_0 and in the manner of evaluating mean properties, it is best to anticipate differences between theory and experiment on the order of a factor of two and to consider the agreement that is seen here as being only qualitative.

The flame shape predictions from the analytical results show good agreement with experiment. Experimental flame measurements appear to be somewhat narrower and longer than predicted, as illustrated in Figure 2 for a particular test. This general trend, observed for most of the comparisons with experiment, may be due to the increase in flame length through finite-rate chemistry downstream as well as variable properties, which are not addressed in the simplified analytical model. The comparisons clearly indicate that, even after optimizing the selection of the value of the diffusion coefficient, flame-shape differences between theory and experiment of at least 20% should be anticipated.

Figure 3 shows the instantaneous radiative heat loss, Q_{rad} , plotted against the instantaneous droplet diameter for n-heptane droplets burning in air with ambient flow velocities ranging from 0 cm/s to 10 cm/s. Average initial droplet diameters were 1.25 mm for the 2 second tower, 2.31 mm for the ZGF, and 3.3 mm for the KC-135. The aggregate plot, showing all results on the same droplet scale, indicate that once the flame transient passes there is an expected convergence in radiative heat loss. It is apparent that tests performed in the ZGF never extended beyond the flame transient where flame expansion relative to the droplet diameter reached a maximum. This is due to the relatively large initial droplet diameters used in these tests and the commensurately short burn time allowed in this facility (i.e., data begins approximately 3 seconds after 0-g ignition and steady velocity was reached). The considerably smaller droplets used in the 2 second tower, coupled with the fact that the drop occurred after ignition, allowed these tests to proceed beyond the flame-expansion period. When results from these tests are plotted separately on a larger scale an interesting observation can be made concerning the relationship between radiative heat losses and flow velocity. Preliminary results indicate that radiative losses tend to decrease as the flow velocity is increased. One possible explanation is that the flame shape becomes increasingly distorted into an ellipsoidal shape with increased flow. The distorted flame shape results in a smaller radiating volume and this, coupled with an increase in convective losses as hot gases are swept downstream, causes a decrease in radiative output from the gas phase. Additionally, decreases in soot radiation resulting from shorter soot residence times due to increased convective effects, also contribute to the observed decrease in radiative output. Recently, we have carried out several experiments with accelerating and decelerating droplets and the results will be presented elsewhere. Some preliminary results can be found in [1].

CONCLUDING REMARKS

Predicted qualitative trends from the asymptotic analysis are supported by experiment. The prediction that the burning rate increases linearly with Reynolds number for small Reynolds numbers is consistent with experiment. The predicted general elongation of the flame in the flow direction and its narrowing transversely are consistent with experiment, but these variations appear to be somewhat more pronounced experimentally, likely because of effects of variable properties and finite-rate chemistry, especially of soot. It may thus be concluded that qualitative

trends may be obtained from the theory, but refinements (introducing greater complexity) are needed for improved quantitative predictions. Experimental results from each of the test configurations show that radiative heat losses from the gas phase contribute to a substantial portion of the overall heat loss mechanism. Additional tests are currently underway to investigate the unsteady effects during convective droplet burning.

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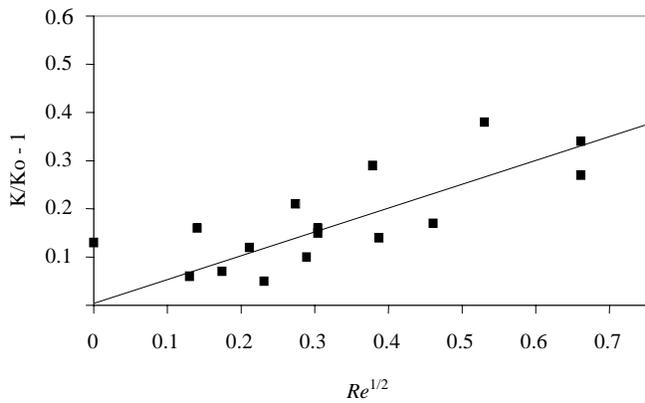


Figure 1. Burning-rate constant vs $Re^{1/2}$ number according to the present theory (line) compared with experimental data (points).

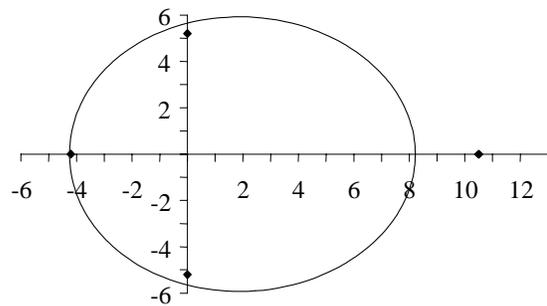


Figure 2. Flame shape for an initial droplet diameter of 1.5 mm, an imposed flow speed of 4 cm/s. The solid line is calculated using the theory while the points represent experimental values.

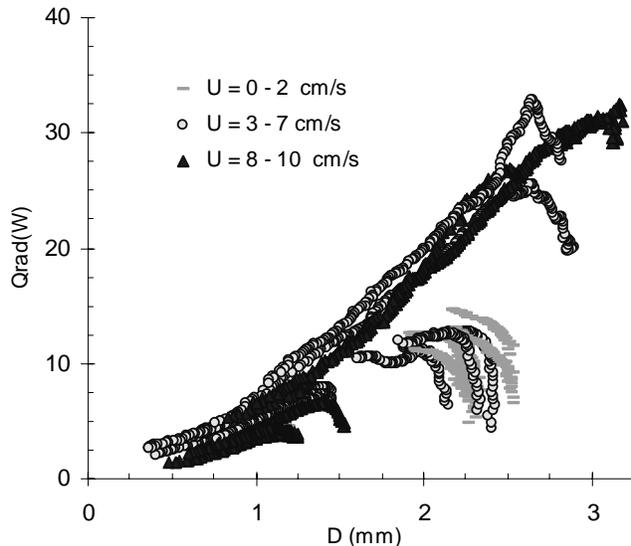


Figure 3. Total radiative flame emission as a function of droplet diameter for various flow velocities during n-heptane burning in air at atmospheric pressure.